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Extreme rainfall, vulnerability and risk: a continental-scale assessment for South America

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Extreme weather continues to preoccupy society as a formidable public safety concern bearing huge economic costs. While attention has focused on global climate change and how it could intensify key elements of the water cycle such as precipitation and river discharge, it is the conjunction of geophysical and socioeconomic forces that shapes human sensitivity and risks to weather extremes. We demonstrate here the use of high-resolution geophysical and population datasets together with documentary reports of rainfall-induced damage across South America over a multi-decadal, retrospective time domain (1960–2000). We define and map extreme precipitation *hazard*, *exposure*, *affected* populations, *vulnerability* and *risk*, and use these variables to analyse the impact

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of floods as a water security issue. Geospatial experiments uncover major sources of risk from natural climate variability and population growth, with change in climate extremes bearing a minor role. While rural populations display greatest relative sensitivity to extreme rainfall, urban settings show the highest rates of increasing risk. In the coming decades, rapid urbanization will make South American cities the focal point of future climate threats but also an opportunity for reducing vulnerability, protecting lives and sustaining economic development through both traditional and ecosystem-based disaster risk management systems.

1. Introduction

Extreme weather continues to preoccupy society, presenting a formidable challenge to public safety, life and the economy. Weather extremes of all kinds constitute 80% of the US$100 billion in global economic damage from natural hazards annually, with tens of thousands of deaths each year and more than 1 billion affected over the last decade from flooding alone [1]. As large as these statistics appear, they understate the full dimension of damage, since there exists no formal accounting system to tabulate social or environmental costs [2]. The potential for substantial economic damage, loss of life and major social disruption justifies a deeper understanding of the underlying geophysical dynamics behind extreme rainfall and flooding and its changing character in statistical terms [3]. Yet, it is the interaction of the physics of extreme precipitation with the geography of human development and societal preparedness that together define the ultimate state of flood-related risk, today and under changing climate [4–7]. Extreme precipitation is thus a quintessential global change and human water security issue.

Attention continues to focus on how global climate change might intensify key elements of the water cycle, including precipitation, run-off and river flows, and how these fluxes could become more extreme [8–12]. Recent work points to the coherence of several lines of evidence supporting the notion that the hydrological cycle is ‘accelerating’, based on both observational and modelling studies (globally [13,14], across the pan-Arctic [15] and in the USA [16]). The issue derives fundamentally from the propensity of the atmosphere to retain increasing amounts of moisture with rising temperature as described by the Clausius–Clapeyron relationship [17]. Greater atmospheric moisture in turn stimulates the intensification of water cycling, which through the dynamics of atmospheric circulation yields not only more intense precipitation but also rainfall shortages and drought. With respect to flooding, accelerated water cycling increases the means and trends in water stocks (tropospheric water vapour content and soil moisture), preconditioning the highly coupled hydrological system to deliver extremes in the fluxes of precipitation and run-off [13,14,18]. Observations have verified theory, showing increased intensity in precipitation worldwide compared with the past half-century [19–22]. At the same time, global atmospheric models capture well this anticipated intensification of precipitation [23]. While not unequivocal, theory, models and observations are thus in general agreement.

From the standpoint of flood risk, such atmospheric changes must be filtered through the terrestrial hydrological cycle. Incongruities in the temporal and spatial overlap of climate and hydrological records, of interpolations of precipitation fields and of gauge bias corrections; limits to how well particular river monitoring stations represent long-term trends; the changing nature of statistical distributions of both precipitation and run-off; and entrenched differences in nomenclature continue to cloud the picture of how extreme rainfall translates into extreme flooding [11,12,24–27]. The realities of quantifying water flows through inherently variable and changing watersheds, defined increasingly by human control of upland landscapes, the widespread disconnection of floodplains from their rivers, as well as large-scale water storage, use and redirection through hydraulic engineering works, obscures the rainfall–flood connection [24,28,29]. Further complications are associated with quantifying antecedent moisture and available storage conditions in watersheds, which play a significant role in flooding through networked pathways that store, mix, attenuate and/or accentuate flows in river corridors. Clear trends in flooding are thus difficult to discern in global [24] and US [30] discharge records, although there is evidence across some regions that low-magnitude floods are increasing in frequency relative to the recent past [31]. Because of these many uncertainties, an unequivocal connection between flooding and observed records of extreme precipitation has yet to be established [20,32].

Studies over the last 10–15 years [26,33–36] have highlighted the need to consider not only geophysics but also the socioeconomic forces that shape human sensitivity to weather extremes. One key phenomenon to quantify and better understand is the propensity of people to settle in hazardous locations. Another is the societal readiness to cope with such events. In the USA, Pielke & Downton [26] and Pielke & Sarewitz [5] circumvented the debate on the direct links of precipitation to flooding *per se* by demonstrating a connection between extreme precipitation and flood damage expressed in economic terms. Their chief finding was that societal factors, namely growth in human population and wealth, were the most important determinants of trends in flood damage, with extreme precipitation taking on a subsidiary role. Ongoing shifts in the magnitude and frequency of floods that result from changes in precipitation may be compounded in coastal cities that face allied threats from river flooding, higher water tables and coastal surges. Vulnerability and risk, and eventually flood disasters, are also tied to thresholds below which little damage occurs, and above which great damage occurs, as demonstrated recently by the contrast in losses across the New York metropolitan area in the wake of Hurricane Irene in 2011 (predominantly rain-induced flooding) versus Hurricane Sandy in 2012 (coastal storm surge) [37–40].

The subject of this study is South America, as part of an effort by the UNESCO Regional Office for Science and Technology for Latin America and the Caribbean (ROSTLAC; Montevideo, Uruguay) to develop frameworks and assessment tools that quantify the impact of changing climate on the continent's populations and economic development. While there were contractual obligations to focus on this continent, South America has several characteristics that lend themselves well to synoptic-scale risk analysis. First, it is a continent with important emerging economies, expanding populations and urban centres, and a rising trend in flood-associated damage. Together with Asia, it shows the highest levels of exposure to sudden-onset weather events [41,42]. Annual population growth rates are about 1%, similar to overall global values, but with an urban growth of 1.5%, falling between that of the most- and least-developed nations. Each of its countries shows a level of development ranging from medium to very high [43], with an overall mean and rate of change in the human development index (HDI) upward and on a par with the global average. And, given that its characteristic levels of the HDI are associated with 74% of all those killed, 92% of all those affected by flooding and 98% of global economic losses [1], analysis of South American flood risk should yield a good cross section of emerging economy sensitivity to extreme events, from which useful generalities can be drawn. The continent is also a good example of how investments in flood mitigation have reduced vulnerability to floods, but at the same time, and in the light of increasing exposure to hazardous conditions, how the overall risk from flooding continues to rise [44]. A parallel study of the Caribbean region can be found in Colon *et al*. [45].

We present here working definitions of extreme precipitation *hazard*, *exposure*, *affected* populations, *vulnerability* and *risk*. We then describe a framework for the *risk* mapping, presenting equations and derived metrics that link geophysical variables with socioeconomic data. The paper goes on to present derived *vulnerability* (damage) functions for urban and rural populations, a geography of precipitation anomalies and then populations *exposed*, *affected* historically and under long-term *risk*. The analysis is continental in scope and spans a multi-decadal period sufficient to discriminate differences among principal sources of threat. We use this capability to rank the principal sources of *risk*, namely geophysical (baseline climate variability or change in climate variability) and socioeconomic (population growth and redistribution) factors that separately (and in tandem) produce observed patterns of damage. We repeat this for total, rural and urban populations. We review and offer advice on how this and other methodologies could be improved to better support assessment and planning efforts. We draw conclusions on societal response to flood risk including a brief discussion on asymmetries in the distribution of preparedness and infrastructure investment across levels of development. We move on to explore alternative, ecosystem-based approaches to flood mitigation with a suggestion for its expanded use in rapidly developing urban settings.

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2. Methodology

There is a rich history of place-based vulnerability assessment (e.g. [46,47]). At the same time, Earth systems science has developed a rapidly expanding arsenal of data products including those from remote sensing, ground-based hydrometeorological networks, data assimilation and simulation that could be used to monitor and analyse the nature of extreme weather over large domains [48–50]. Many datasets are global in extent yet at resolutions useful in monitoring local environmental conditions [51] and supporting flood early warning systems [48]. It is less clear how these geospatial datasets could be applied in broad-scale vulnerability assessment and development planning because they have seldom been combined in such context [50,52–54]. Studies by Dilley *et al.* [55] and Balk *et al.* [7] are noteworthy exceptions, each executing an *a posteriori* mapping of natural hazards, combining geospatial hazard extent maps with documented loss statistics.

We combine here high-resolution geophysical and population datasets with documentary evidence to analyse the impact of damaging floods using a risk-based approach. When these events are quantified in terms of their statistical frequencies as reflected by different levels of extreme precipitation or hydrological state (e.g. rainfall anomaly, river flood stage) and combined with population maps, an aggregate measure of *exposure* to *hazard* can be obtained. When these exposure frequencies are further combined with damage or *vulnerability* functions that link particular anomaly magnitudes to recorded or assumed levels of asset damage or human loss, an estimate of societal *risk* can then be computed. This overall strategy guides our approach as detailed below.

We use a probabilistic approach to mapping risk, based on established (though not universally adopted; see Birkmann [56], Cutter [57]) definitions of *hazard*, *exposure*, *vulnerability* and *risk* [47,56, 58,59] plus the combination of both documentary and geospatial datasets. We adopt normalized anomalies as a measure of potentially damaging precipitation [26], defining *hazard* (H) as a monthly rainfall event (r_{net}) benchmarked to the climatological monthly mean

$$H = \frac{r_{\text{net}}}{\bar{r}_{\text{net}}}, \tag{2.1}$$

The risk-producing hazards take many forms—flooding of course, but also excessive erosion and associated landslides and mudslides. Both means and monthly anomalies in local rainfall (r_{local}) were routed downstream through a digital river network and redefined as r_{net} based on a hyperbolic function, which was determined by the sum of all sources of upstream local rainfall and contributing area a_c ($r_{\text{net}} = \sum r_{\text{local}}/a_c$). Our definition for H is closely related to that for *geological hazard* given in the United Nations International Strategy for Disaster Reduction (UNISDR) [60]. *Exposure* is the total number of people in contact with a particular level of H during a time step, and is expressed as

$$E_H = P|H, \tag{2.2}$$

where P is population. *Affected* populations (A) are those experiencing damage, expressed in absolute terms. While we recognize that the notion of *affected* populations requires standardization and further refinement [35] and that there is under-reporting [1,61] even in the USA [62], we believe that we derived usable and intuitively consistent vulnerability relations based on event reports judged to be reliable.[1] *Vulnerability* (V) is the proportion of E that is *affected*

[1]From www.cred.be, defined as: 'People requiring immediate assistance during a period of emergency, i.e. requiring basic survival needs, such as food, water, shelter, sanitation and immediate medical assistance'. Vulnerability relations were based on data from the Center for Research on the Epidemiology of Disasters International Disaster Database (www.cred.be). In our analysis, we include reported deaths as a component of people affected. Relatively small events with fewer than 2000 individuals affected were removed from the analysis. A total of 213 events, reported monthly, were used from 1960 to 2000.

(decimal fraction, 0–1) by each level of H, over the entire time and spatial domain,

$$V_H = \overline{A/E}|H, \tag{2.3}$$

where V_H is the degree of loss conditioned on a given hazard category H. This degree of loss can also be quantified in financial terms, such as property damage, or in per cent of people displaced, killed or injured.

Risk (R) is the mean proportion of the population that is affected (defined as the expected losses in the study of Downing *et al*. [47]) over a specified time period. The risk (R_A) in absolute terms can be determined by multiplying vulnerability V_H by the exposed population E_H and the probability (Pr) of a specific hazard H

$$R_A = \sum_{i=1}^{n_\mathrm{h}} [V_{H_i} \times E_{H_i} \times \Pr(H_i)], \tag{2.4}$$

where n_h is the number of hazard categories. The probability of a given hazard category, $\Pr(H_i)$, is estimated as its relative frequency over the historical record.

Both R and R_A represent aggregate measures over the entire period of record (1960–2000) and reflect a full inventory of the reported damage. However, the *risk* values also can be reported over monthly or annual time periods, and normalized to give relative levels of risk over space. The probabilistic notion of *risk* associated with these definitions can be found in earlier studies [63–65].

Operationally defining these concepts requires reconciliation of administrative-level reports (given at monthly time intervals) and geospatial variables. Our approach determines changing spatial patterns of H, V, E and R using a 40 year time series of gridded precipitation [66], urban/rural population [67] and digital river networks [68] (figure 1), together with reports on populations affected (figure 2). Documentary evidence on damaging flood events was drawn primarily from reports at the state or national administrative level (see footnote 1).

We assume that the footprint of extreme precipitation extends well beyond the locally detected anomaly and is conditioned upon both local flooding caused by extreme rainfall and the delivery of any associated excess run-off through river networks impacting adjacent, inhabited lowlands and floodplains. The use of routed precipitation anomalies obviates the need for an explicit hydrological model capable of capturing the dynamics of short-term flood events, which typically can last for periods much shorter than the monthly interval of the damage reports. The network-conditioned anomaly time series was used in conjunction with administrative unit damage reports to generate unique vulnerability relationships for urban and rural populations. The coping and adaptive capacity of countries to hydrological extremes is reflected implicitly in the derived statistical relationships of the V functions presented below, which are undifferentiated at the continental scale.

Rainfall–damage relationships were constituted from individual event reports. For each event, pixel-based values for $r_\mathrm{net}/\bar{r}_\mathrm{net}$ were computed, ranked over administrative unit and used to develop a cumulative population distribution over the corresponding report domain. From each of these distributions, the total population *affected* was identified, assuming that damage was associated with the highest networked anomalies, using a retrograde counting procedure (figure 3). Values of $r_\mathrm{net}/\bar{r}_\mathrm{net}$ were binned using 0.2 unit increments. E and A were tabulated for each bin over the entire period and for the entire continent ($n \approx 2.8 \times 10^5$ cells; $6'$ latitude/longitude, 64 km^2 mean area), and then expressed as the fraction $\overline{A/E}(=V)$. We used 213 reported events (see footnote 1), affecting more than 35 million people to generate rural and urban V functions. To enable consistent mapping and intercomparison across South America, we applied a single threshold of approximately 400 inhabitants km^{-2} to distinguish high-density (hereafter, urban) from low-density (rural) populations (cf. United Nations [6] giving multiple definitions).

The V–H relationships (figure 4) show a rise in potential damage as a function of increasing rainfall anomaly, with the form of these *vulnerability* functions bearing strong resemblance to those found in other impact studies of extreme weather [42,64]. For both urban and rural V, an apparent threshold exceeding 1% damage is noted when $r_\mathrm{net}/\bar{r}_\mathrm{net}$ reaches approximately 1.6, with some

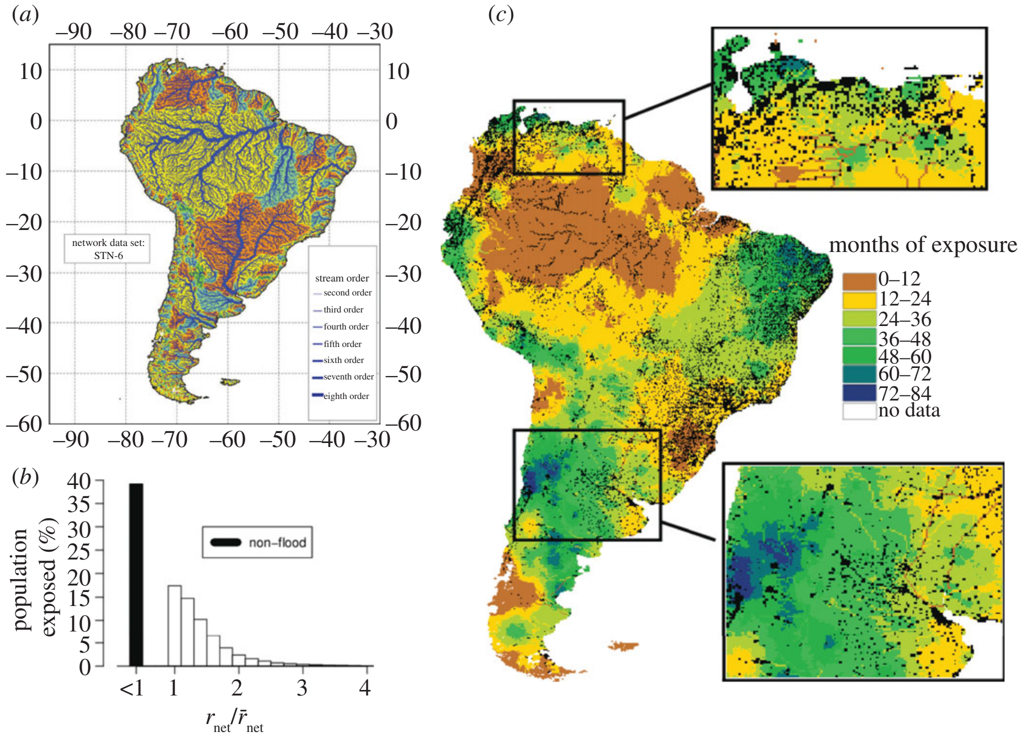

Figure 1. Biogeophysical datasets used in this analysis. (*a*) Map of 6′ (longitude × latitude) resolution river network; (*b*) relative distribution of *exposed* populations to rainfall anomaly categories over the 40 year period; (*c*) population along with the number of months of *exposure* over the 40 year period to anomalies greater than 2× (one measure of *hazard H*). Insets show in greater detail the 1 km population distribution and the *hazard* anomalies networked through river corridors. Climate and population time series are from [66] and [67], respectively. STN, *simulated topological network* [68].

additional indication that urban settings show differential sensitivity to low levels of anomaly, but are more resilient at higher levels of *H*. Both relationships show a saturation at the highest levels of anomaly, an apparent self-limitation in damage tied to the relatively smaller spatial scales of the highest anomaly events and the effectiveness of flood attenuation through river networks.

3. Geography of exposure and risk

The rainfall and population time series applied in conjunction with the *vulnerability* functions for each *H* class (figure 4) yields a geography of *exposure* and *risk* in response to extreme precipitation. We emphasize that our methodology is designed to uncover continental-scale tendencies, not to predict individual events at specific locations. Much of the continent shows a high degree of *exposure* to potentially damaging precipitation. One expression of this phenomenon is a continental geography of the number of months of rainfall *hazard H*, exceeding 2× the mean normal value (figure 1*c*), which allows for a spatial comparison of greater than average rainfall regions and sub-regions resulting from differences in the skewness of precipitation distributions. From this mapping, we see that the wet tropics, in particular Amazonia, shows fewer such events, reflecting the relatively more even temporal pattern in its precipitation regime. Higher frequencies of *H* are seen in Western Argentina/Chile, in the region surrounding Santiago and the Andes, as well as in northeastern Brazil, two comparatively drier areas with more seasonally distinct and episodic rainfall patterns. The map also shows sharp gradients in precipitation anomalies, for example in Venezuela, which over very short distances shows more variable versus evenly distributed rainfall patterns. An aggregate measure of *H* is the mean areal extent of local monthly

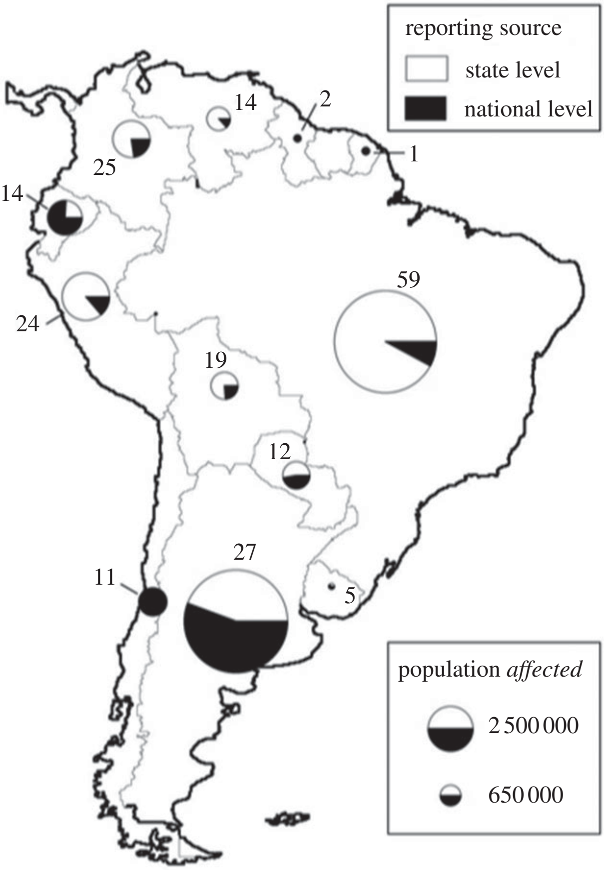

Figure 2. Number of reported events and number of people *affected* by those events, presented by country. Documentary reports from CRED/EM-DAT (see footnote 1) are at the country or at the sub-country state level, as shown.

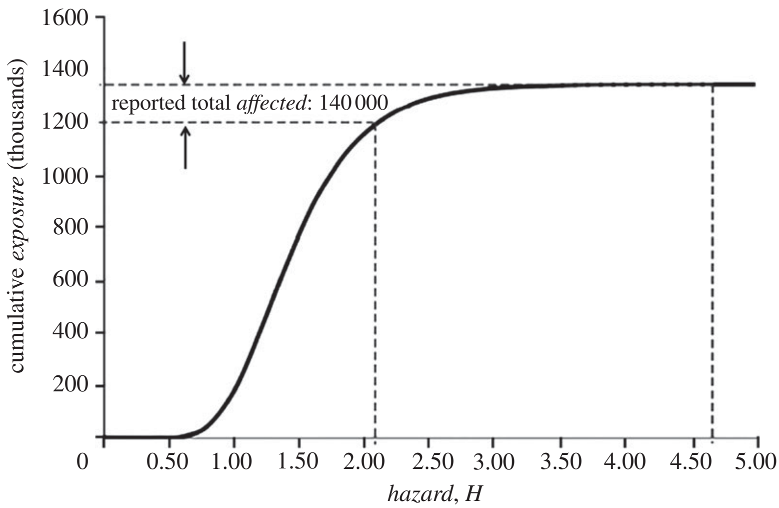

Figure 3. Idealized, cumulative *exposure* of population (E) as a function of increasing *hazard* level ($H = r_{\text{net}}/\bar{r}_{\text{net}}$) for an individual documented precipitation event. The retrograde counting technique seeks to identify the rainfall threshold for damage, assuming that the highest H anomalies are associated with the populations reported to be affected by the event. We started at the highest level of H, identified its associated E, tabulated the result and repeated the process across sequentially lower H values until the total population *affected* as reported in the administrative unit report was met (in this case 140 000).

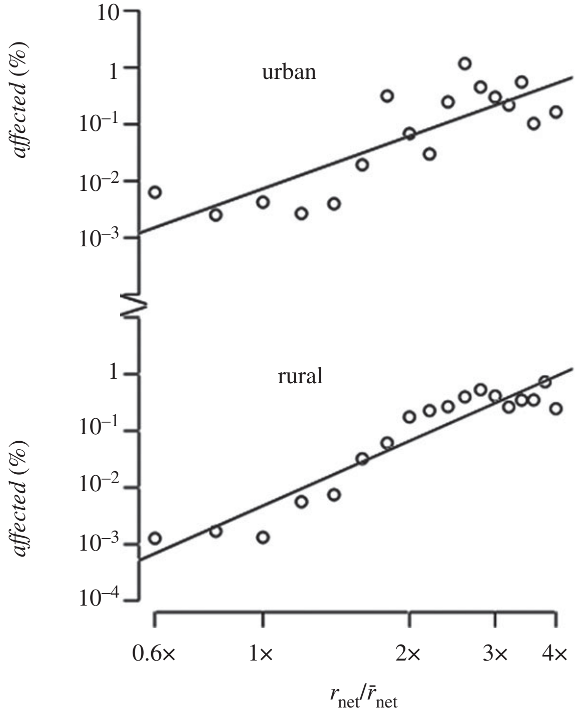

Figure 4. *Vulnerability* functions for urban and rural areas resulting from the conjoined geospatial and administrative unit datasets. Percentage refers to the proportion of those populations *exposed*.

rainfall anomalies, which for 2× normal rainfall spans 884 000 km^2 (4.9% of South America land area) and for 4× normal rainfall only 57 000 km^2 (0.3%). Superimposed on these H patterns are high-resolution population distribution estimates (figure 1*c*), which are necessary to compute the overall level of *exposure* E. Our calculation procedures that embody diminishing probabilities of the most extreme of rainfall rates yield a sequentially smaller number of people likely to be *exposed* to higher levels of H, which figure 1*b* confirms.

While the degree of absolute *risk* is certainly underestimated (our analysis is limited by the completeness, or lack thereof, of documentary reports on numbers *affected* as explained earlier), the relative spatial distributions of high and low values for R_A are instructive (figure 5*b*). Repeated (monthly) *exposure* over the 40 year period (figure 1*c*) was most extreme in Argentina (San Juan, La Pampa, Mendoza, La Rioja) and Chile (Region Metropolitana). High levels of *exposure* result in high levels of *risk* R_A, which are apparent for a broad arc of states along the eastern coast, from Buenos Aires in the south to eastern Amazonia in the north. The geography of R_A shows a high-level aggregate impact along this Eastern flank of the continent, including the states of Buenos Aires, São Paulo, Rio de Janeiro, Ceara and Pernambuco, each with large urban centres. High impact is also shown in northeastern Brazil, including states in the dry east and relatively wet state of Para. Together these states have relatively high population densities (89 versus 15 inhabitants km^{-2} for the rest of the continent) and high rainfall variability (mean coefficient of variability (CV) = 1.08 versus 0.76 more generally).

The pattern shifts substantially when the *risk* is expressed as rates of loss in units of percentage of total population *affected* (R), with areas of such *risk* extending to both sides of the continent and into several climate zones (figure 5*c*). The highest degree of R is in dry regions (coastal Venezuela, central Chile, eastern Patagonia and Pampas in Argentina, northeastern Brazil), characterized by more episodic rainfall. Transition zones between wet and dry regions (Gran Chaco in Paraguay/Argentina, northern Venezuela/Colombia) show intermediate levels of R. By this measure, areas within the Brazilian Amazon and southeastern Brazil are relatively safe

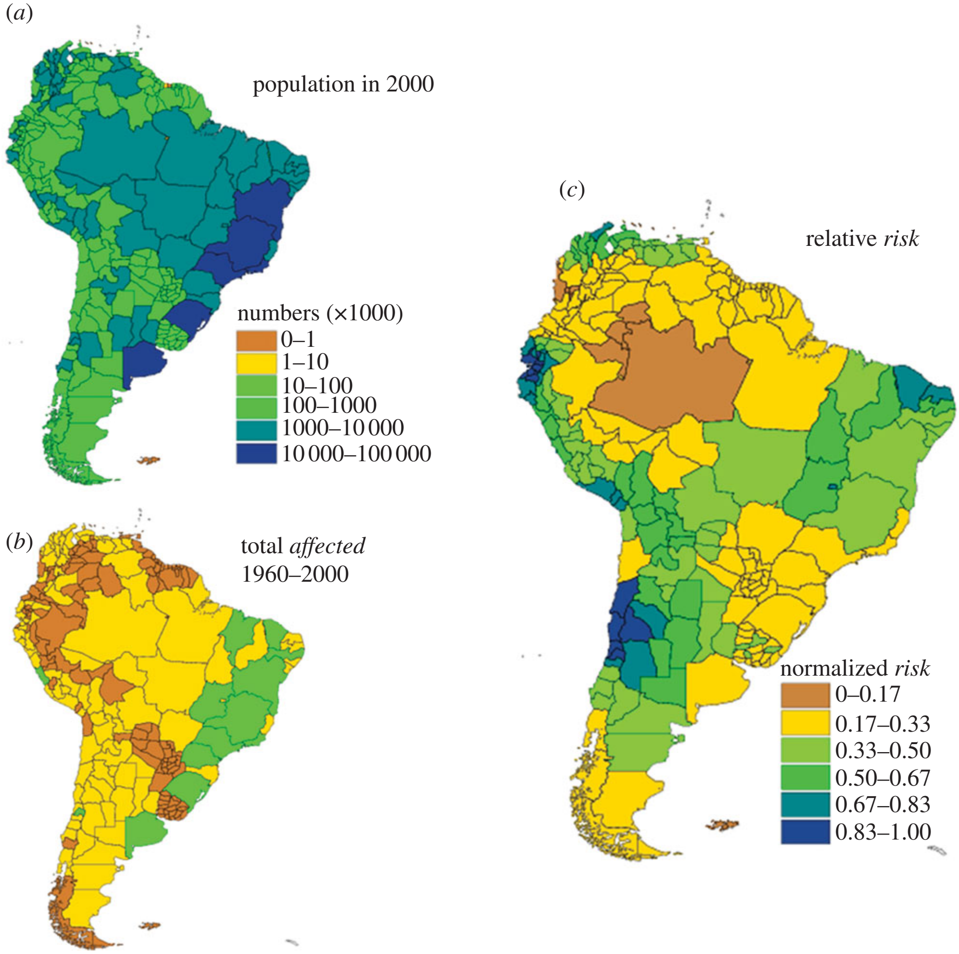

Figure 5. State-level estimates of (*a*) total administrative unit population in the year 2000, (*b*) predicted number *affected* (R_A; equation (2.4)) over the 40 year period and (*c*) predicted relative *risk* (*R*, normalized as in [69]). Predictions take into account the probability of an anomalous precipitation event occurring and the *vulnerability* of the population given such anomalous events over the period of record.

places to live with respect to rainfall extremes, a consequence, at least in part, of less frequent and extreme precipitation anomalies (figure 1*c*, with CV of rainfall = 0.57 versus 0.89 for the rest of the continent). Our result for southeastern Brazil predates the reality that significant floods were registered in the last decade (e.g. Blumenau municipality in Santa Catarina state in 2008 and the whole area of the Itjai Valley) [70], highlighting the fact that our methodology is designed to uncover continental-scale tendencies, and not to predict individual events at specific locations.

4. Origins of risk

The distribution of *affected* populations (i.e. absolute *risk* R_A) was further analysed to determine the major sources of aggregate damage over the period 1960–2000. A baseline climate period was defined as 1960–1970 together with a baseline population fixed at 1960 levels and 1960 geographical distributions. The model was run for the full 40 year period, but repeating the initial 10 year climate record. Against this benchmark, we formulated three scenarios, similar to the approach used in Vörösmarty *et al.* [67], to isolate climate impacts on water stress. Under the first scenario (Sc1), climate was allowed to vary as in the observational record [66], whereas population was fixed at the 1960 level. The second scenario (Sc2) used the 1960–1970 climate cycle as in the baseline but enabled urban and rural populations to grow and redistribute spatially, as they did historically. The third scenario (Sc3) allowed both variables to change (i.e. climate and population as observed).

Consistent with the *risk* definitions described earlier, we accounted for and spatially redistributed all 35.6 million people as reported in the events database (see footnote 1) to be affected by extreme rainfall over the full period of record. While we argued earlier that the documentary reports provide an estimate of but a sub-set of all populations affected by extreme rainfall, these reports span all countries across the continent, provide both rural and urban population damage assessments, and represent a large number of climate zones. We therefore deemed them adequate for the purpose of this sensitivity experiment, that is, to identify sources of extreme precipitation *risk* in relative terms.

We find that approximately one-half of all damage (49%; R_A of 17.5 million) is associated with baseline climate variability in the context of 1960 (baseline) population distributions (table 1), suggesting that, in aggregate, the risk environment that evolved over the continent from 1970 to 2000 was no more or less capable of generating damage than conditions that existed in the first decade of the experiment. With respect to the incremental sources of impact from 1970 to 2000 (18.1 million), two-thirds are derived from population growth and about one-fifth from changing climate variability, with a smaller interaction effect noted as well.

These overall results mask differential impacts across rural and urban settings (table 1). Compared with the urban setting, rural populations show a greater absolute impact during the 1960–2000 period, derived mainly from baseline conditions (13 million *affected*). Smaller net increases in R_A (an additional 9.3 million *affected*) emerged from all sources of incremental change (i.e. local, spatially differentiated population growth and redistributions, enhanced climate variability and their interaction). We thus see a 60–40 split, with baseline conditions predominating over the incremental change. Relative to baseline, all of the incremental changes jointly produce a 72% increase in numbers affected, with population contributing about 60% and climate 30% to the increment. These results suggest that among rural populations baseline variability has been the predominant factor producing *risk*, with demographic changes next most important, and climate change *per se* producing the least effect.

While showing less overall impact in absolute terms (i.e. smaller R_A) compared with the rural condition, urban populations displayed the most rapid change in *affected* populations, nearly twice the baseline condition (8.7 versus 4.5 million). Most of the incremental change (6.7 million) can be traced to urban population growth, constituting over three-quarters of the increase. Climate change again takes on a subordinate role, constituting less than 10% of the incremental change. For the 380% increase in the number of new urban dwellers we calculate for South America from 1960 to 2000, there is a corresponding increase of 193% in risk measured through *affected* populations, a near tripling in the number affected. Urban areas are thus the predominant focal point for changing patterns of extreme event damage across the continent, with population growth leading the way in terms of overall impact on *risk*.

5. Discussion and conclusions

While differing from this study in time domains covered and particular datasets employed, the recent work of Dilley and co-workers [55,69], UNISDR [44] and Balk *et al.* [7] connecting historical patterns of floods to documented losses has set important benchmarks for more detailed geospatial risk analysis. As explained earlier, this study employs a similar approach to its risk-based assessment, but is distinct by focusing on South America, linking the climate forcing of precipitation anomalies directly to damage (a geospatial equivalent to the study of Pielke & Downton [26] and Pielke & Sarewitz [5]), considering a longer 40 year record, basing *exposure* and *risk* estimates on *hazard* anomalies routed through digital river networks, and differentially developing urban and rural *vulnerability* functions. All of these geospatial studies use ad hoc methods to identify event probabilities, apportion damage consistent with documentary accounts

Table 1. Aggregate, continental-scale *risk* (damage) totals from extreme precipitation, relative contributions to *risk* and relative sources of incremental *risk* from 1960 to 2000 for total, urban and rural populations in South America.

source of *risk*[a]	number *affected* (absolute *risk* R_A) (millions)	relative contribution to aggregate damage (%)	increase relative to baseline (%)
total population			
baseline[b]	17.5	49	
all other changes[c]	18.1	51	103
climate change	3.6	10	21
population change	12.0	34	69
interaction	2.5	7	14
total	35.6	100	
rural population			
baseline[b]	13.0	58	
all other changes[c]	9.3	42	72
climate change	2.8	13	22
population change	5.3	24	41
interaction	1.3	6	10
total rural	22.4	100	
urban population			
baseline[b]	4.5	34	
all other changes[c]	8.7	66	193
climate change	0.8	6	18
population change	6.7	51	149
interaction	1.2	9	27
total urban	13.2	100	

[a] Climate and population time series from [66] and [67], respectively.
[b] Baseline used a fixed 1960 population plus climate variability between 1960 and 1970.
[c] Referred to as 'incremental change(s)' in the running text.

and map *risk*. In the case of Balk *et al*. [7] (using flood information from UNISDR's [44] 2009 report), flood frequencies over a 100 year time frame were developed from much shorter 21 year records and documentary evidence from CRED for 1980–2000, missing entries replaced with a single specified value, and hazard estimates supplemented by and further calibrated to a 9 year record from the Dartmouth Flood Observatory. Dilley *et al*. [55] also used the period 1980–2000 for the documentary reports, but then 1985–2003 for flood hazard, assigned an additional regional and national wealth index, and accounted for multiple exposures.

An essential common denominator in all these geospatial studies is the documentary evidence of damage, yet these reports are based today on a finite number of samples and an admixture of information sources that is surely an incomplete record of all possible damage-producing precipitation events. The approaches likewise depend on an accurate assessment of flood potential and hydrological extremes, whether it be flooded areas detected by remote sensing (i.e. Dartmouth Flood Observatory) or rainfall anomalies routed through digital river networks (this study). As reports continue to accumulate, the situation will improve but will also confront the perennial challenge of descoped and defunded hydrographic monitoring across much of the world [71] and fragmentary, unstandardized damage reports [72–74]. Reconciling the inherent spatial distortions of using administrative unit reports when floods follow hydrologically meaningful boundaries poses an important technical challenge [75].

Our purpose here is to neither criticize nor advocate for any particular method, but rather to point out that these approaches have yet to be harmonized. In the context of new geospatial risk models, we do suggest the value of executing a suitable intercomparison exercise, which has proved to be of great value in other scientific domains [76–78]. Among several benefits, an intercomparison study would help to unify input datasets, resolutions, time steps and time domains; create carefully controlled numerical experiments; and, design diagnostics to understand differences across contrasting methodologies.

Once problems have been adequately diagnosed, the issue of minimizing flood risk can turn to suitable interventions. Establishing human water security in the light of weather extremes is part of a broader, global investment strategy in the water sector totalling US$0.5–0.75 trillion per year and relying heavily on technology and traditional engineering [29,79]. Damage is ultimately tied to investments in flood preparedness, warning systems and response capacity of both a structural (e.g. flood mitigation reservoirs, levees) and non-structural (e.g. upstream land management, forecasts and telecommunications) nature [2,44,80]. Thus, the distribution of such readiness is concentrated most heavily in developed nations, placing much of the developing world at risk from a lack of investment or, should investments actually be made, financial indebtedness [42,55,81]. Nonetheless, in the light of rising flood risk [44], countries across South America are today investing in flood warning systems [82,83]. Reservoir storage is one traditional measure of the capacity of societies to cope with climate extremes. Yet, orders of magnitude separate the poor and the rich, as in the case of Ethiopia, which on a *per capita* basis has 150 times less reservoir storage than North America. The country suffers a corresponding loss of annualized gross domestic product (GDP) of 40% owing to this lack of infrastructure that could otherwise insulate it against both flooding and drought [84]. By contrast, annual flood impacts in the USA have typically been much less than 1% of GDP [85].

At the same time, heavy reliance on traditional flood protection systems such as large flood control dams or levees represents a ‘hard path’ water strategy, costly in terms of financial investments and ecosystem health [29,86,87] but attractive from the standpoint of yielding perceived high returns on investment (e.g. 6-to-1 in the USA [85]). To varying degrees, such investments ultimately replace the free public services conveyed by natural wetlands [88]; specifically, floodplains and riparian zones acting as hydraulic shock absorbers, absorbing excess water in times of heavy inundation and releasing it slowly upon flood recession. Yet, the disconnection of rivers from their floodplains is today pandemic, with a majority of pixel-based accounting units (30′ latitude/longitude) showing evidence of fragmentation [29]. Innovative use of green infrastructure that simultaneously offers flood protection and preserves important ecosystem services such as fish and wildlife habitat, biodiversity and the self-purification potential of inland waterways has yet to be adopted broadly [89]. In the disaster assessment community, protection and active use of wetlands (and upland watersheds) is central to integrated ecosystem-based risk management strategies [44]. A recent review of several structural and non-structural flood control measures places the economic returns of floodplain restoration at over 100 : 1, an order of magnitude higher than traditional structural engineering investments and even greater than early warning systems [90]. The US Army Corps of Engineers, arguably best known for massive hydraulic engineering works, also employs floodplains as a building block in its overall flood control strategy [85].

While results from our study indicate that the sensitivity of rural populations in South America to flooding remains substantial, urban areas are the foci for most rapid growth in risk. With continued rural-to-urban migration, and rapid and generally poorly managed infrastructure development, South American cities showed a near doubling in absolute risk from 1960 to 2000. Rapid population growth and urban development in the context of historical climate variability were the major factors shaping South America’s risks to extreme rainfall. Although we did not explicitly consider future conditions, our results suggest that this is likely to remain so at least over a decadal time frame, supporting Bertoni's [36] contention that the continent's cities will be the foci of future vulnerability to extreme rainfall and flooding.

While developing world cities are incubators for uncontrolled urban growth and increasing risk [91,92], they also could prove to be valuable test grounds for innovation in flood risk management, capitalizing on inherent economies of scale and the potential comparative advantage in governance that go along with densely populated settlements [44,93], which are believed to have led to an overall reduction in disaster vulnerability historically across South America [44]. While climate change and human development will both increase the level and complexities of risk, new strategies are needed to develop and retrofit climate-resilient cities. The challenge is to fight the growing infrastructure deficit [92] separating rich and poor by harnessing technology, innovative engineering solutions and ecosystem-based risk reduction in a cost-effective manner. To some degree, the challenge may be less formidable insofar as investments in new infrastructure will inevitably be made as part of the ongoing urbanization process. The challenge therefore becomes one of steering these new investments into more flood-resilient designs for the built environment.

A capacity to map the patterns of *risk* and to develop a clearer understanding of the sources of potential damage from extreme rainfall and flooding will be essential to the design of adaptation strategies that protect life and the substantial investments currently being made in sustainable development throughout the developing world. This study confirms previous work based primarily on documentary evidence that shows societal risk to be derived from the combination of natural and social factors. In this context, much work has yet to be achieved. Inability to establish and detect thresholds to damage, incongruities in the operational definition of terms such as *vulnerability*, differences in time domains analysed, and an admittedly incomplete documentary record will continue to frustrate development of approaches that could ultimately unite geophysical approaches with the human dimensions of risk. The challenge in quantifying the differential readiness to prepare for, flee, and rebuild after floods also persists. Developing flood-resilient South American cities, from the purely utilitarian perspective of protecting the largest numbers of people, presents not only a challenge but also a unique opportunity to combine innovative engineering and ecosystem-based risk reduction strategies. Newly built infrastructure, protected and rehabilitated green infrastructure, better enforced regulation and compliance, and expanded flood warning systems could all be marshalled to the task of containing extreme weather and flood risk. Judging from the politicization of the broader climate change question to which flood risks are intimately connected, the societal commitment to do so remains an open question.

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